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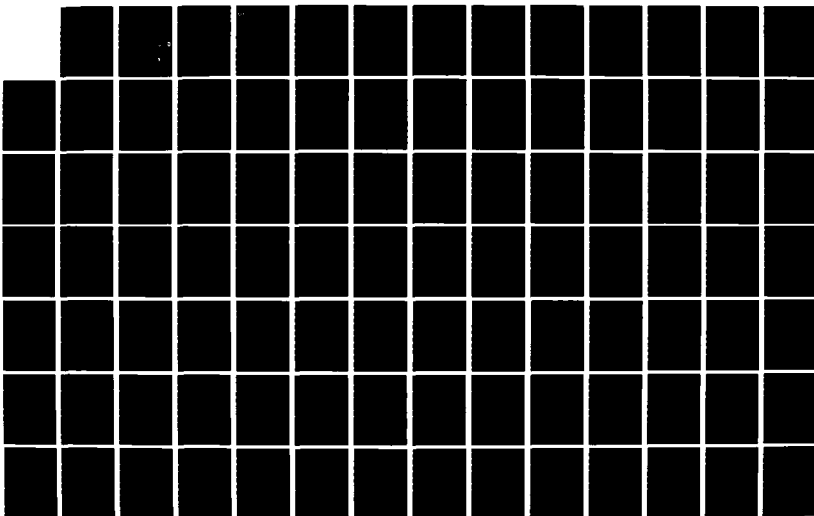
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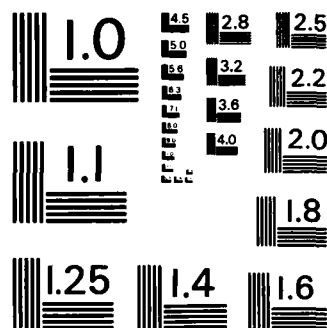
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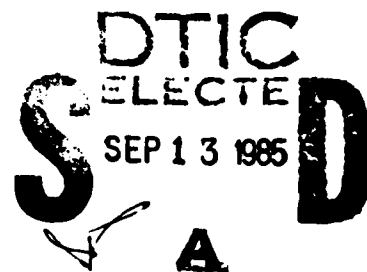


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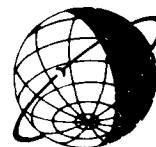
# GLACIOLOGICAL DATA

ISSN 0149-1776

## MARGINAL ICE ZONE BIBLIOGRAPHY



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DEPARTMENT OF THE NAVY  
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IN REPLY REFER TO

3910  
Ser 425AR/211  
11 September 1985

MEMORANDUM

From: G. L. Johnson, ONR Code 425AR  
To: Jan Jarus, DTIC/AB, BLDG 5, Cameron Station, Alexandria, VA 22304  
Subj: PHONE CONVERSATION OF 10 SEP 85

1. As per our phone conversation on 10 SEP 85, this verifies that the Marginal Ice Zone Bibliography from World Data Center A was supported by ONR funds and therefore qualifies for your data bank.

A handwritten signature in cursive script, reading "G. L. Johnson", is written over a horizontal line.

G. L. JOHNSON  
Acting Head, Geophysical Sciences

**June 1985**

## DESCRIPTION OF WORLD DATA CENTERS<sup>1</sup>

WDC-A: Glaciology (Snow and Ice) is one of three international data centers serving the field of glaciology under the guidance of the International Council of Scientific Unions Panel of World Data Centers. It is part of the World Data Center System created by the scientific community in order to promote worldwide exchange and dissemination of geophysical information and data. WDC-A endeavors to be promptly responsive to inquiries from the scientific community, and to provide data and bibliographic services in exchange for copies of publications or data by the participating scientists.

1. The addresses of the the three WDCs for Glaciology and of a related Permanent Service are:

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World Data Centre C  
Scott Polar Research Institute  
Lensfield Road  
Cambridge, CB2 1ER, England

Permanent Service on the Fluctuations  
of Glaciers  
Swiss Federal Institute of Technology  
CH-8092 Zurich, Switzerland

2. Subject Matter

WDCs will collect, store, and disseminate information and data on Glaciology as follows:

Studies of snow and ice, including seasonal snow; glaciers; sea, river, or lake ice; seasonal or perennial ice in the ground; extraterrestrial ice and frost.

Material dealing with the occurrence, properties, processes, and effects of snow and ice, and techniques of observing and analyzing these occurrences, processes, properties, and effects, and ice physics.

Material concerning the effects of present day and snow and ice should be limited to those in which the information on ice itself, or the effect of snow and ice on the physical environment, make up an appreciable portion of the material.

Treatment of snow and ice masses of the historic or geologic past, or paleoclimatic chronologies will be limited to those containing data or techniques which are applicable to existing snow and ice.

3. Description and Form of Data Presentation

3.1 General. WDCs collect, store and are prepared to disseminate raw<sup>+</sup>, analyzed, and published data, including photographs. WDCs can advise researchers and institutions on preferred formats for such data submissions. Data dealing with any subject matter listed in (2) above will be accepted. Researchers should be aware that the WDCs are prepared to organize and store data which may be too detailed or bulky for inclusion in published works. It is understood that such data which are submitted to the WDCs will be made available according to guidelines set down by the ICSU Panel on WDCs in this Guide to International Data Exchange. Such material will be available to researchers as copies from the WDC at cost, or if it is not practicable to copy the material, it can be consulted at the WDC. In all cases the person receiving the data will be expected to respect the usual rights, including acknowledgement, of the original investigator.

<sup>1</sup>International Council of Scientific Unions. Panel on World Data Centers. (1979) Guide to International Data Exchange Through the World Data Centres. 4th ed. Washington, D.C. 113 p.

<sup>+</sup>The lowest level of data useful to other prospective users.

This Guide for Glaciology was prepared by the International Commission on Snow and Ice (ICSI) and was approved by the International Association of Hydrological Sciences (IAHS) in 1978.

3.2 Fluctuations of Glaciers. The Permanent Service is responsible for receiving data on the fluctuations of glaciers. The types of data which should be sent to the Permanent Service are detailed in UNESCO/IASH (1969)\*. These data should be sent through National Correspondents in time to be included in the regular reports of the Permanent Service every four years (1964-68, 1968-72, etc.). Publications of the Permanent Service are also available through the WDCs.

3.3. Inventory of Perennial Snow and Ice Masses. A Temporary Technical Secretariat (TTS) was recently established for the completion of this IHD project at the Swiss Federal Institute of Technology in Zurich. Relevant data, preferably in the desired format\*\*, can be sent directly to the TTS or to the World Data Centers for forwarding to the TTS.

3.4. Other International Programs. The World Data Centers are equipped to expedite the exchange of data for ongoing projects such as those of the International Hydrological Project (especially the studies of combined heat, ice and water balances at selected glacier basins\*\*\*), the International Antarctic Glaciological Project (IAGP), and Greenland Ice Sheet Project (GISP), etc., and for other developing projects in the field of snow and ice.

#### 4. Transmission of Data to the Centers

In order that the WDCs may serve as data and information centers, researchers and institutions are encouraged:

4.1. To send WDCs raw<sup>+</sup> or analyzed data in the form of tables, computer tapes, photographs, etc., and reprints of all published papers and public reports which contain glaciological data or data analysis as described under heading (2); one copy should be sent to each WDC or, alternatively, three copies to one WDC for distribution to the other WDCs.

4.2 To notify WDCs of changes in operations involving international glaciological projects, including termination of previously existing stations or major experiments, commencement of new experiments, and important changes in mode of operation.

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\*UNESCO/IASH (1969) Variations of Existing Glaciers. A Guide to International Practices for their Measurement.

\*\*UNESCO/IASH (1970a) Perennial Ice and Snow Masses. A Guide for Compilation and Assemblage of Data for a World Inventory; and

Temporary Technical Secretariat for World Glacier Inventory. Instructions for Compilation and Assemblage of Data for a World Glacier Inventory.

\*\*\*UNESCO/IASH (1970b) Combined Heat, Ice and Water Balances at Selected Glacier Basins. A Guide for Compilation and Assemblage of Data for Glacier Mass Balance Measurements; and

UNESCO/IASH (1973) Combined Heat, Ice and Water Balances at Selected Glacier Basins. Part II, Specifications, Standards and Data Exchange.

<sup>+</sup>The lowest level of data useful to other prospective users.

## FOREWORD

This issue provides a major bibliography on sea ice, meteorology and oceanography in the marginal ice zone. It has been recognized in the last few years that processes of air-ice-ocean interaction occurring near the boundary of ice-covered seas are of critical importance to our understanding of the mechanisms of seasonal ice growth and decay and short and long term anomalies in ice extent. Oil and gas exploration and development are increasingly being conducted in areas with seasonal ice cover and the ice margin is also a zone of high productivity by marine biota. Until recently, opportunities to conduct research in the marginal ice zone (MIZ) were limited by available technology, but a major international marginal ice zone experiment (MIZEX) is underway in the Bering Sea and the East Greenland Sea and results from this work are now beginning to appear in the literature. The National Snow and Ice Data Center (colocated with WDC-A for Glaciology) is providing data management services for the MIZEX-East program and we anticipate that sometime in the future, data sets collected during MIZEX may become available to other interested users.

We are also pleased to include in this issue a contribution from Dr. W. Stinger, University of Alaska, on sea ice morphology and characteristics, based on chapter 1 of the recently published Handbook for Sea Ice Analysis and Forecasting (Naval Environmental Prediction Research Facility, Monterey, California, 1984).

Data entry work for this issue was undertaken by Carol Pedigo, and the entire material was edited by Ann Brennan of the Data Center staff.

R.G. Barry  
Director  
World Data Center-A for Glaciology  
(Snow and Ice)  
and National Snow and Ice Data Center

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# Sea Ice Morphology and Characteristics

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Fairbanks, Alaska, U.S.A.

## SECTION 1. FORMATION AND DEVELOPMENT OF SEA ICE

### 1.1 THE FREEZING PROCESS

1.1.1 Freezing Point of Sea Water.  $0^{\circ}\text{C}$  is defined as the melting point of freshwater ice. Conversely, fresh water can start freezing when it is at  $0^{\circ}\text{C}$ . Dissolving salts in water lowers its freezing temperature. Sea water contains approximately 35‰ (35 parts per thousand or 3.5 per cent) dissolved salts, most of which is sodium chloride or common table salt. This quantity of salts is sufficient to depress the freezing point of sea water to around  $-1.9^{\circ}\text{C}$ . When applying this concept, it should be remembered that in many nearshore areas, particularly bays and lagoons fed by freshwater streams, the salt concentration in the water is less than 35‰ and its freezing point is correspondingly higher.

1.1.2 Supercooling of Water Before Ice Formation. Water does not actually freeze precisely at its melting point (although the difference can be extremely small). This results from the fact that freezing is a change of phase (as is the transition of water into water vapor). This phase change alone requires the withdrawal of 80 calories per gram of water ( $3.3 \times 10^5 \text{ kJ/kg}$ ). This is a tremendous amount of energy considering that 1 calorie is defined as the amount of heat required to raise or lower one gram of water by  $1^{\circ}\text{C}$ . Thus, it requires the withdrawal of just as much energy to create one gram of freshwater ice at  $0^{\circ}\text{C}$  as it would to lower the temperature of that gram of water from  $80^{\circ}\text{C}$  to  $0^{\circ}\text{C}$ .

At first, one might think that the only way to satisfy this energy requirement ( $80 \text{ cal g}^{-1}$ ) would be to cool the entire quantity of water to be frozen to  $-80^{\circ}\text{C}$  before it would suddenly freeze into ice at  $0^{\circ}\text{C}$ . But this is not the case. After the water temperature has been lowered sufficiently below its freezing point (supercooled), small crystals of ice form and the heat of fusion is released into the surrounding water. Thus,

although heat of fusion has been expelled from the water freezing into small ice crystals, it has merely warmed up the surrounding water. No energy need enter or leave during the freezing process.

1.1.3 Frazil Ice Formation. The process of supercooling takes place continuously in freezing water. The small crystals thus formed grow into small disc-shaped platelets of ice with dimensions on the order of 1 or 2 mm in diameter and thickness in the vicinity of 1/10 the diameter. These platelets become the fundamental building blocks of newly forming sea ice. They are nearly pure freshwater ice; the dissolved salts having been excluded during the growth of the crystals into frazil platelets. Clearly, this increases the salt concentration in the remaining water.

1.1.4 Water Density. Here we must introduce the concept of the temperature of maximum density as a function of salinity. First, we will consider the density of fresh water as a function of temperature. Fresh water contracts upon cooling until it reaches 4° C; when cooled further it expands. As a result, when a lake is cooled, the cooled surface water at first sinks towards the bottom because the cool water is heavier than warm water. If water were like most liquids which continue to become heavier with decrease in temperature, a cooled lake would continue to cool until the whole lake was at its freezing point, then it would begin to freeze. If water in its solid state were heavier than in its liquid state (again like most materials), then newly forming ice would accumulate at the bottom and the lake would freeze from the bottom to the top. Many northern lakes would freeze completely and never thaw except for a surface layer.

Fortunately, as explained above, water is most dense at 4° C and expands when cooled further. Furthermore, ice expands significantly when it freezes (on the order of 10%) so that its solid phase floats. The result of this is that after our hypothetical lake has reached 4° C, water cooled even further - being lighter than the 4° C water - does not sink but remains on the surface. Hence, the bulk of the lake remains at 4° C as ice formation takes place on its surface. After that, additional ice forms on the bottom of the ice surface.

Sea water is a different matter. As salts are added to water, both the temperature of maximum density (starting at 4° C) and the freezing



point (starting at 0° C) are depressed. However, the temperature of maximum density decreases faster with salt concentration than does the freezing temperature. These two temperatures coincide at roughly 25% salt concentration. Water with greater salt concentration (such as sea water at 35%) does not reach a maximum density before it freezes. (It does, of course, expand upon freezing.) As a result, the entire sea water column down to some depth requires cooling all the way to the freezing temperature before freezing takes place near the surface. The depth of this cooling depends on several factors including natural layering within the ocean, the surface cooling rate, and wind stress on the water surface. Naturally occurring density layering (as a result of temperature and salinity) tends to limit the depth of mixing. Very low temperatures can cause rapid cooling of the surface layer and its freezing before mixing at depth can occur. Wind stress, on the other hand, tends to increase the mixing depth.

1.1.5 Frazil Ice Depth. Because of the mixing of cooled sea water, it is possible that supercooling and frazil ice formation can take place within a mixed surface layer (at least a meter or two, and perhaps considerably deeper in some situations). Hence, at the very beginning of freezeup of sea water, small frazil discs form as a result of supercooling within the top layer of the ocean. Frazil ice then becomes the basic building material for the ice forms which follow.

Another way in which the ocean becomes saturated with ice crystals is for snow to fall into an ocean cooled to below 0° C. Since the salt water is cooler than the melting point of the snow crystals, they accumulate as slush which forms a viscous floating mat.

## 1.2 STAGES OF ICE GROWTH BEYOND FRAZIL AND SLUSH

In this section we will follow sea ice terminology through the nomenclature of terms describing the various stages of growth from frazil crystals to thick first-year ice.

1.2.1 New Ice. This term includes all categories up through a thickness of 10 cm. New ice not only includes frazil and slush ice, but also several other ice types. For the sake of completeness, all ice types in this category will be described here.

1.2.1.1 Frazil Ice. Frazil ice represents the first stage in the freezing process. It consists of fine needles or platelets of ice, suspended in sea water.

1.2.1.2 Slush. Slush consists of snow which has saturated and mixed with the water creating a viscous floating mass of ice crystals within the water. Thus, slush represents an independent process by which ice crystals can be introduced into cold sea water.

1.2.1.3 Grease Ice. This is the next stage in ice formation beyond frazil ice. At this point, the frazil crystals have coagulated to form a soupy layer on the sea surface. Grease ice reflects less light than water and has a dark matte appearance. Grease ice forms regardless of sea state, but tends to increase in thickness with sea agitation.

1.2.1.4 Shuga. With a large degree of wind stress and accompanying wave agitation, grease ice or slush collects into spongy white lumps a few cm in diameter. This ice type is called shuga.

1.2.2 Nilas. As freezing continues, grease ice undergoes a transition to nilas, a thin (up to 10 cm) elastic crust with a matte surface. The only exception to this transition is in cases where the sea state and wind stress are sufficient to cause the formation of shuga (described in 1.2.1.4). When placed under a confining pressure, nilas is easily thrust into a pattern of interlocking fingers called finger rafting. Nilas is divided into two subcategories:

1.2.2.1 Dark Nilas. Nilas which is under 5 cm in thickness and is very dark in appearance.

1.2.2.2 Light Nilas. Nilas which is between 5 and 10 cm in thickness and is lighter in appearance than dark nilas, but not quite gray.

1.2.3 Ice Rind. This ice develops in areas where water with less salinity than sea water is found. As a result, it forms a brittle, shiny crust either by direct freezing (as on a fresh water pond) or from grease ice. This stage continues for thicknesses up to 5 cm. Because it is brittle, it is easily broken up, usually into rectangular pieces, by wind and gentle waves.

2.5.1 Standing Floe. A single floe standing vertically or inclined to the ice surface and surrounded by relatively smooth ice.

2.5.2 Rafted Ice. Ice which has been forced to override other ice as a result of compression. Although rafting is most common among thinner forms of ice, there have been reports of rafted ice 2 m thick overlapping by over 100 m in the horizontal.

2.5.3 Hummock. A hillock of broken ice which has been forced upward by pressure.

2.5.4 Hummock Field. A collection of hummocks. A hummock field which has survived one or more melt seasons is called a second-year or multiyear hummock field. Such older hummock fields can form large, thick and relatively strong floes.

2.5.5 Ridge. A line or wall of ice forced up by pressure. A ridge can vary in length from a few hundred meters to over a hundred kilometers. Many observers make a distinction between a pressure ridge which appears as a relatively short, somewhat irregular pile of ice and a shear ridge which appears as a sinuous mound of piled ice stretching relatively long distances across the ice. Shear ridges are created as a result of differential motion between two regional ice bodies (often the drift ice against fast ice). Very often a shear ridge consists of many parallel bands of piled ice, some with vertical walls 2 to 3 m in height. Pressure ridges are more local in nature and result from purely compressional forces within the ice. Ridges may be divided by age in the following way:

2.5.5.1 New Ridge. The ice blocks are simply piled together. Sharp blocks are piled at roughly a 40° angle of repose.

2.5.5.2 Consolidated Ridge. A ridge which has been exposed to sufficient cooling that its base has frozen together.

2.5.5.3 Aged Ridge (also known as second-year or multiyear ridge). A ridge which undergoes a melt season has brine drained from much of its ice. Furthermore, fresh melt water from the ridge sail (the exposed upper portion) tends to freeze together the ice blocks composing the keel of the ridge. This process continues with each melt season with the result that the ridge becomes stronger, both as a result of the filling of

2.3.5.2 Concentration Boundary. A line approximating the transition between two regions having different drift ice concentrations.

## 2.4 TERMS DESCRIBING THE APPEARANCE OF THE ICE SURFACE

### 2.4.1 Snow-Related Factors.

2.4.1.1 Bare Ice. Ice without snow cover.

2.4.1.2 Snow-Covered Ice. Ice with snow cover. Snow-covered ice is usually more white in appearance than bare ice during winter months, regardless of thickness. As a result, a snow cover on ice makes estimating its thickness very difficult.

2.4.2 Melt Season Factors. As the summer season approaches, the occurrence of water on the ice surface causes a sequence of events resulting in a changing appearance of the ice.

2.4.2.1 Puddled Ice. At the beginning of the summer season melt water from snow and ice accumulates on the ice surface, presenting a pattern of dark patches. Ice at this stage is referred to as puddled ice.

2.4.2.2 Flooded Ice. This term is used to refer to ice that is largely covered with water, either from extensive melt water or river water spread upon the ice.

2.4.2.3 Dried Ice. Eventually the flooded ice drains through cracks and thaw holes developed in the ice. The drained ice whitens considerably. Large portions of floes remain wet and many areas of open water now occur. The white portions of the ice are called dried ice.

2.4.2.4 Rotten Ice. The term rotten ice refers to ice during an advanced stage of melting. Very little ice still maintains sufficient freeboard to appear white. Most of the ice surface is wet and the ice is honeycombed.

## 2.5 TERMS RELATED TO SEA ICE STRUCTURES

The terms in this category generally derive from compressional forces within sea ice which results in ice raised above the normal ice surface. Although sizes of these features can vary, the presentation here will be generally in order of increasing size.

2.3.2.2 Belt. A drift ice field which is considerably greater in length than width is called a belt. The width of a belt can vary between 1 and 100 km. Ice of any size or age may be contained.

2.3.3 Terms Used to Define Pronounced Features in the Boundary Between an Ice Field and the Surrounding Water.

2.3.3.1 Tongue. This term is used to describe a projection of an ice field into the adjacent ocean area with a markedly lower ice concentration. Tongues are often caused by winds or currents and are sometimes transformed into a swirl-like structure.

2.3.3.2 Bight. An indentation in an ice edge. As with tongues, their topological opposites, bights are often caused by winds and currents.

2.3.4 Terms Involving the Extent of Ice.

2.3.4.1 Ice Edge. This term is used to denote the boundary between ice of any concentration or type and the open sea. It can be described as compact or diffuse depending on how well defined it appears.

2.3.4.2 Ice Limit. This term is based on a statistical computation of the extreme minimum or extreme maximum location of the ice edge for a given period (for instance, the month of March) over a period of several years. The term "ice limit" is preceded by either minimum or maximum.

2.3.4.3 Mean Ice Edge. As with ice limit, the mean ice edge is a statistical term. The mean ice edge is simply the average position of the ice edge as measured over some specified period of time.

2.3.4.4. Mean Maximum or Mean Minimum Ice Edge. This term is used to denote the geographical location of the average of the extreme summertime or wintertime locations of the ice edge over a period of years. These two statistical locations are often indicated in atlases.

2.3.5. Terms Describing Boundaries Within The Ice.

2.3.5.1 Fast Ice Boundary. This term is used to denote the boundary at any time between the fast ice and drift ice. (If no drift ice were present, it would be called the fast ice edge.)

2.2.4 Flaw. Strictly speaking, the flaw is the line of fracture between the fast ice and drift ice when they are in close proximity. A variety of conditions can be found associated with such a flaw. It may consist of a series of polynyas along the fracture separated by linear regions where drift ice has been piled into a shear ridge (see 2.5.5). Such a flaw is generally created when the drift ice is driven along the fast ice edge with a component of compressive force (thus creating a "shear") between the two ice masses. There may be regions of the flaw filled with brash ice and there may be signs of freezing of ice to the new or young stage within the polynyas if the shearing motion responsible for formation of the flaw has ceased.

## 2.3 TERMS DESCRIBING THE PHYSICAL ARRANGEMENT OF SEA ICE

Sea ice can be found in a variety of arrangements. A series of distinctive terms has been defined to aid the description of sea ice in narrative accounts and messages.

### 2.3.1 Terms to Describe the Size of an Agglomeration of Floating Ice.

2.3.1.1 Ice Patch. An area of floating ice less than 10 km in horizontal dimension.

2.3.1.2 Ice Field. An area of floating ice with dimensions greater than 10 km. Size distinctions are:

small ice field: 10 to 15 km

medium ice field: 15 to 20 km

large ice field: greater than 20 km

ice massif: a large ice field which is found in the same general location every summer.

### 2.3.2 Terms to Describe the Configuration of a Patch or Field.

2.3.2.1 Strip. A strip is defined as a long, narrow (1 km or less) patch or field of drift ice and often consists of brash ice and sometimes new ice forms. Strips are often generated as smaller ice fragments are detached from the main body of drift ice and run together under the influence of wind, waves, or swell.

they could be rejoined to form a solid sheet of ice. Fracture Zone describes an area with a great number of fractures. Often the fractures in a fracture zone have a regular pattern resulting from stress having been applied somewhat uniformly over a large area. Terms based on width of fracture are as follows:

<u>crack:</u>	<1 m (One specific type, <u>tidal crack</u> , is between the ice foot and the floating fast ice.)
<u>very small fracture:</u>	1-50 m
<u>small fracture:</u>	50 - 200 m
<u>medium fracture:</u>	200 - 500 m
<u>large fracture:</u>	wider than 500 m.

2.2.2 Polynya. A polynya is an irregularly shaped opening enclosed by ice. As opposed to a fracture, the sides of a polynya could not be re-fitted to form a uniform ice sheet. Polynyas may contain brash ice or uniform ice of markedly thinner ice than the surrounding ice. Terms based on a polynya's location or persistence are as follows:

2.2.2.1 Shore Polynya. A polynya located between drift ice and the coast or between the drift ice and an ice front (ice front defined in 2.6.2.3).

2.2.2.2 Flaw Polynya. A polynya located between drift ice and fast ice.

2.2.2.3 Recurring Polynya. A polynya which occurs at the same location every year.

2.2.3 Lead. A lead is a fracture through sea ice sufficiently wide to permit navigation by surface vessels. As with polynyas, some leads are defined in terms of their location:

2.2.3.1 Shore Lead. A lead located between drift ice and the shore or between drift ice and an ice front.

2.2.3.2 Flaw Lead. A lead located between drift ice and fast ice.

2.1.2.2.2.2 Consolidated Pack Ice. Pack ice in which the concentration is 10/10 and the floes are frozen together.

2.1.2.2.2.3 Very Close Pack Ice. Pack ice in which the concentration is 9/10 to less than 10/10.

2.1.2.2.2.4 Close Pack Ice. Pack ice in which the concentration is 7/10 to 8/10 composed of floes mostly in contact.

2.1.2.2.2.5 Open Drift Ice. Drift ice in which the ice concentration is 4/10 to 6/10 with many leads and polynyas and the floes are generally not in contact with each other.

2.1.2.2.2.6 Very Open Drift Ice. Drift ice in which the concentration is 1/10 to 3/10 and water preponderates over ice.

2.1.2.2.2.7 Open Water. A large area of freely navigable water in which sea ice is present in concentrations less than 1/10 and no ice of land origin is present.

2.1.2.2.2.8 Bergy Water. An area of freely navigable water in which ice of land origin is present. There may be sea ice present but the total concentration shall not exceed 1/10.

2.1.2.2.2.9 Ice Free. No ice present. If ice of any kind is present, this term should not be used.

## 2.2 ICE TERMS BASED ON BREAKS OR OPENINGS IN THE ICE

Openings or breaks within the ice can be very important from the points of view of transportation or operations upon the ice cover and navigation through the ice. For this reason, a number of terms are used to describe in a specific way openings in terms of width, location, and navigability.

2.2.1 Fracture. This term, rather than lead (defined below) is the basic descriptor of openings or breaks within the ice. A fracture is defined as any break or rupture through fast ice, pack ice with concentration 9/10 or greater, or even a single floe. The length of a fracture can vary from less than one m to many km. In cases where fractures have a finite width, they may contain brash ice and/or be covered with nilas and/or young ice. In general, the two sides of a fracture appear as if



Below, several other forms of oceanic ice are defined which are largely independent of development stage.

2.1.2.1.2 Ice Breccia. This is an ice condition that results from several cycles of ice breaking into pieces and the freezing of the voids created between the pieces. The result is an expanse of ice pieces of different ages (and, therefore, most likely different thicknesses) frozen together.

2.1.2.1.3 Brash Ice. This term is used to describe accumulations of floating ice made up of fragments not more than 2 m in largest dimension.

2.1.2.1.4 Ice Cake. This term is used for a piece of relatively flat ice not more than 20 m in its largest dimension. Small Ice Cakes are ice cakes less than 2 m in horizontal extent. Hence, brash ice is composed of small ice cakes.

2.1.2.1.5 Ice Floe. This term describes any piece of ice, regardless of age, more than 20 m in dimension. Floes are subdivided in terms of size:

<u>small floe</u> :	20 - 100 m
<u>medium floe</u> :	100 - 500 m
<u>big floe</u> :	500 - 3,000 m
<u>vast floe</u> :	2 - 20 km
<u>giant floe</u> :	greater than 10 km.

#### 2.1.2.2 Drift Ice Terms Based on Percent Cover.

2.1.2.2.1 Ice Cover is the ratio of an area of ice of any concentration to the total area of sea surface within some large geographic region; this may be global, hemispheric, or prescribed by a specific oceanographic entity such as Baffin Bay or the Barents Sea.

2.1.2.2.2 Concentration is the ratio expressed in tenths, describing the mean areal density of ice in a given area.

2.1.2.2.2.1 Compact Pack Ice. Pack ice in which the concentration is 10/10 and no water is visible.

tast ice is broken loose and transported away, the ice foot generally remains in place.

2.1.1.3. Grounded Ice. Grounded ice can occur within the floating fast ice or as individual pieces of ice grounded in shoal waters. For instance, grounded ridges and hummocks (see Sea Ice Structures, 2.5) can occur within the floating fast ice. In such cases, they act to even further stabilize the fast ice. The remnants of hummocks and ridges can remain in nearshore areas well into the melt season. These are sometimes called stamuki. Islands of grounded ice can occur on shoals located beyond the fast ice. Stranded ice consists of ice which had been floating, but has been deposited on land exposed by retreating water.

2.1.1.4 Anchor Ice. Regardless of the nature of its origin, ice which is submerged or attached to the ocean bottom is called anchor ice.

2.1.2 Drift Ice generally replaces the historical term pack ice. It is a very broad category which includes any area of sea ice other than fast ice regardless of its form or arrangement. If freshwater ice is present it is called floating ice. The term pack ice may be used at concentrations of 7/10 and higher. We have already described many terms used to describe the development of drift ice. There are two other series of terms describing drift ice; one series is based on size and appearance of ice pieces and the other is based on percent ice cover.

2.1.2.1 Drift Ice Terms Based on Size and Appearance.

2.1.2.1.1 Pancake Ice. This ice consists of roughly circular pieces of ice from 30 cm to 3 m in diameter, and up to 10 cm in thickness. The pancakes have a raised rim as a result of their striking up against each other. They develop either on a slight swell from grease ice, shuga, or slush or as a result of large swells breaking up previously formed nilas or even thicker forms. Pancake ice is actually a form that new and young ice can assume over a range of thicknesses. On the other hand, it can be such a major stage in the development of ice cover that we have already listed it under development categories (see 1.2.4).

## SECTION 2. FORMS, TYPES, AND CONDITIONS OF ICE

In the previous section we discussed ice terms based largely on age and stage of development. However, there are other terms used to describe sea ice in reference to the size of individual pieces, its mobility, the arrangement of the ice, the nature of openings in the ice (in a macroscopic sense) and other factors.

### 2.1 ICE TYPES BASED ON MOBILITY CHARACTERISTICS

Regardless of age, oceanic ice can be divided into two broad categories based on its ability to move. These types are fast ice and drift ice.

2.1.1 Fast Ice is defined as sea ice which has formed along or has become attached to the shore, shoals, or to the seaward margins of glaciers. Although the ice is not moving horizontally with respect to shore, it may undergo vertical fluctuations resulting from changes in sea level. Fast ice can form in place or result from the attachment to shore and consolidation of individual floes of any age. It may extend a few meters or several hundred km from shore. Fast ice can be of any age and may be described in age terms (young, first-year, second-year or multiyear). If it has a freeboard greater than two meters, it is called an ice shelf. (Note: A freeboard of two meters implies a total thickness of around 20 meters.) The following terms are used to describe fast ice:

2.1.1.1 Young Coastal Ice. This term is used to depict early stages of fast ice. The ice has usually progressed to the nilas or young ice stage. However, it should be emphasized that ice this thin can easily be detached from shore and later stages of fast ice may not develop from a particular occurrence of young coastal ice.

2.1.1.2 Ice Foot. As fast ice grows in thickness, a narrow fringe of ice along the shore becomes frozen to and even into the bottom. This fringe is called the ice foot. There is usually a series of tidal cracks separating the ice foot from the floating fast ice which rises and falls with sea level changes. This crack region is often referred to as the hinge between the ice foot and the floating fast ice. If the floating

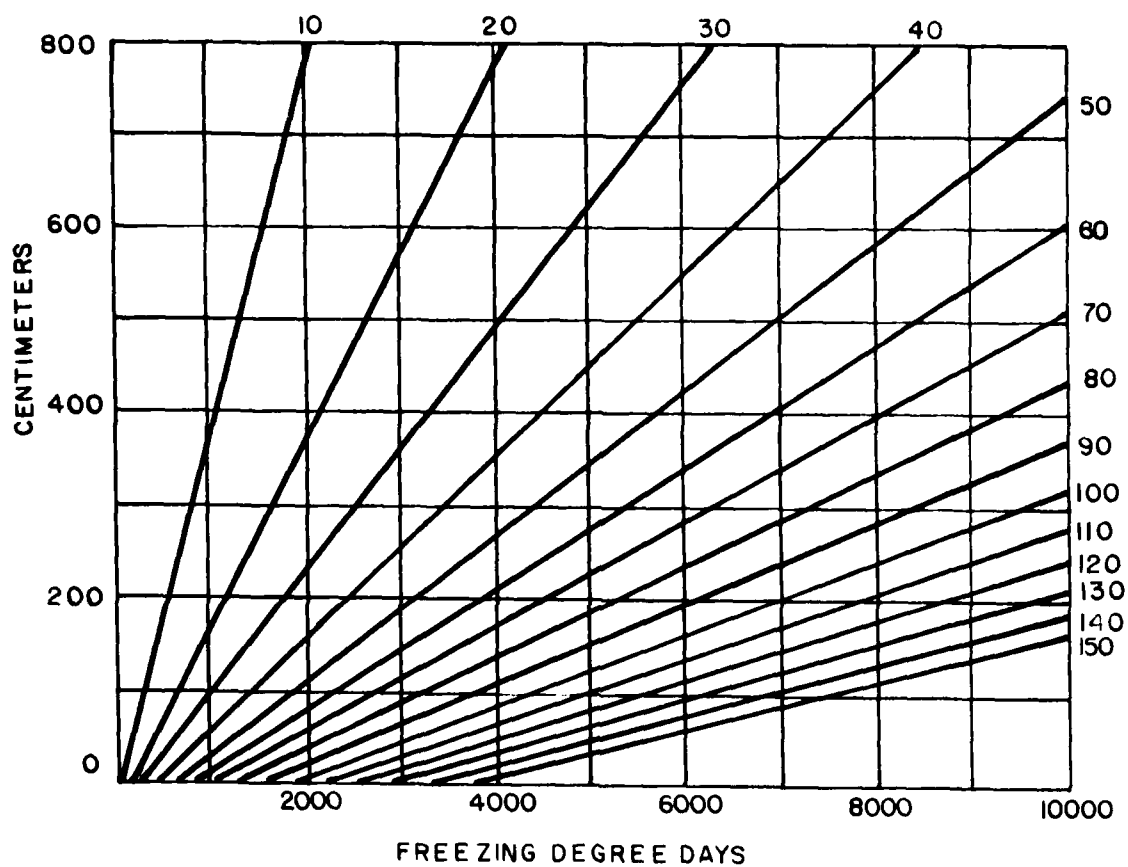


Figure I-2. Graph for computing ice thickness growth (cm) along the slanted lines, in terms of number of freezing degree days (°C on the x-axis) and initial ice thickness (cm on the y-axis).

top of the ice limits the heat conduction through the ice and, therefore, its rate of growth and final thickness. The heat conductivity of snow is approximately 1/10 that of ice. Hence, a 10 cm layer of snow on the ice surface would reduce heat transport as much as 1 m of additional ice.

The factors discussed above vary from place to place and with season. However, it is possible to standardize these environmental conditions somewhat by describing the ice growth in terms of accumulation of freezing degree days. (The number of degrees Celsius that the mean temperature for a given day is below freezing, summed over the number of days under consideration.) On-site measurements of the growth of ice related to freezing degree days produced the curves shown in Figure I-2 (Zubov, 1943). Figure I-2 shows the incremental growth in ice thickness in terms of thousands of freezing degree (°C) days for a range of initial ice thicknesses. For example, in order to determine how much growth will occur when ice 100 cm thick is subjected to 5000 freezing degree days, simply move along the graph horizontally at the value of 100 on the y-axis until the value of 5000 is reached on the x-axis. These coordinates intersect at the growth increment value of 110 cm.

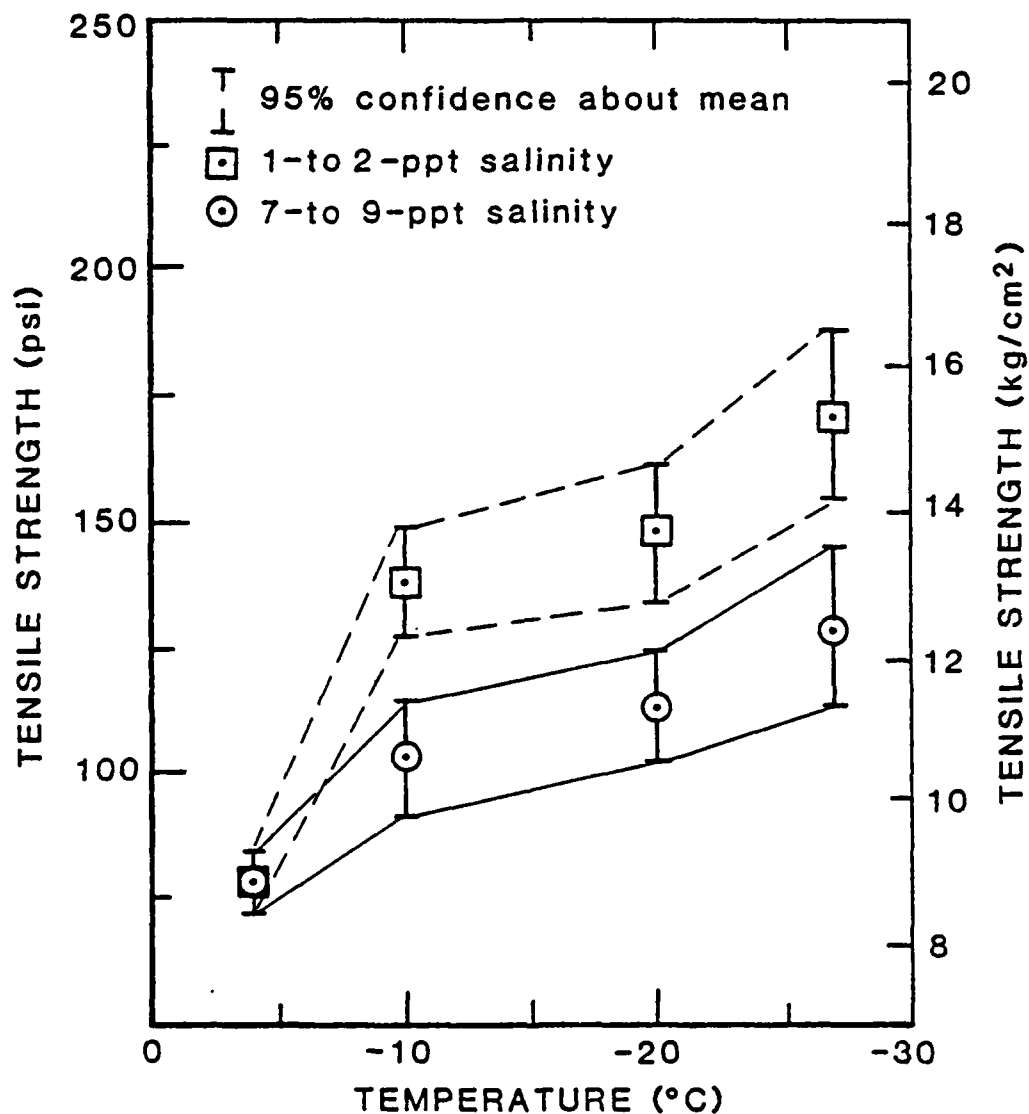


Figure I-1. Shown are results of Dykins (1971) comparing sea ice tensile strength as a function of temperature and salinity. Two salinity ranges were used: 1 to 2 parts per thousand (corresponding to multiyear ice) and 7 to 9 parts per thousand (corresponding to young ice). Envelopes about data points demonstrate data variability.

second-year ice, while ice which has survived more than one melt season is called multiyear ice. The reason that a distinction is made for ice surviving a melt season is because of ice strength. When ice forms, the overall salt concentration may be considerably less than sea water (on the order of 6%) with most of this salt residing as very salty water trapped in the form of brine pockets. The water in these pockets has a very low freezing point due to its high salt content. Because of the pockets, the ice remains considerably weaker than fresh water ice. However, the strength does increase with decreasing temperatures. By  $-5^{\circ}\text{C}$ , its strength is roughly 75% that of fresh ice.

During the first melt season many of these brine pockets are drained by migration to the underside of the ice or flushed by melt water passing through the ice, leaving the ice considerably less saline. Fig. I-1 shows the change of strength of ice with two salt concentrations as a function of temperature. From this figure, it can be seen that as temperatures decrease, old ice will increase in strength earlier than young ice. Furthermore, old ice is stronger than young ice at any given temperature. See section 3.3.1 for further discussion.

### 1.3 ICE THICKNESS GROWTH RATE

Having discussed the range of ice types from frazil to first-year thick, it is worthwhile to consider the rate at which ice grows in thickness. Clearly, for ice to grow on the bottom surface of a floe, heat must be removed from its top surface. In general, therefore, the rate of ice growth is proportional to the rate at which heat can be transferred away from the ice and into the atmosphere. Heat transfer is proportional to the temperature difference between the top and bottom surfaces of the ice and the conductivity of the ice, and is inversely proportional to the thickness of the ice.

Thus, we expect ice to grow fastest when the air above it is coldest and when the ice is thin. Everything else being constant, we would expect the growth rate of ice to decrease with increasing ice thickness. In fact, one would expect the growth of ice to cease when equilibrium is reached between the rate at which heat is removed from the top of the ice and the rate at which heat is supplied to the underside of the ice from the water below. Finally, because snow acts as an insulating blanket, snow on the

1.2.4 Pancake Ice. (Pancake ice is not truly a thickness category, but it has been included here because it can be a major stage in the development of sea ice.) This ice consists of roughly circular pieces of ice from 30 cm to 3 m in diameter, and up to 10 cm in thickness. The pancakes have a raised rim as a result of their striking up against each other. They develop either on a slight swell from grease ice, shuga or slush or as a result of large swells breaking up previously formed nilas or even thicker forms.

1.2.5 Young Ice. This is ice in the transition stage between nilas and thicker forms. Its thickness ranges between 10 and 30 cm. It is subdivided into gray ice and gray-white ice.

1.2.5.1 Gray Ice. Young ice 10-15 cm thick. It is less flexible than nilas and often breaks under swell (becoming a candidate for pancake ice). It is still sufficiently thin that it will raft under pressure.

1.2.5.2 Gray-White Ice. Young ice 15-30 cm thick. Under pressure, it is more likely to ridge (i.e. break up and form a pile of broken ice) rather than raft.

1.2.6 First-Year Ice. As young ice grows in thickness beyond a thickness of 30 cm, it is called first-year ice. However, this category can be broken down into the following subcategories:

1.2.6.1 Thin First-Year or White Ice. This ice is sufficiently thick to appear white as opposed to the gray appearance of young ice. Its thickness ranges between 30 and 70 cm and is sometimes divided into a first stage (30-50 cm) and second stage (50-70 cm). Although there have been occasional reports of rafting of ice this thick, it usually ridges under pressure.

1.2.6.2 Medium First-Year Ice. This is first-year ice 70-120 cm in thickness.

1.2.6.3 Thick First-Year Ice. This is first-year ice with thickness greater than 120 cm.

1.2.7 Old Ice. This general term is used to describe ice more than one melt season old. Ice which has survived one melt season is called



voids and the rejection of salt. During this process the surface appearance of the ridge becomes less angular and more gently-sloped.

2.5.6 Floeberg. This is a massive piece of ice, either a hummock field or a portion of a massive ridge system which has become frozen together. Floebergs with freeboards of 5 m have been observed.

## 2.6 TERMS RELATED TO GLACIAL ICE STRUCTURES AND FEATURES

### 2.6.1 Sources.

2.6.1.1 Glaciers are created by the accumulation of snow. There are a number of glacial forms. However, in all cases the accumulated snow is metamorphosed into ice through a process of compression, thawing and refreezing, and water vapor transport. The glacial ice then slowly advances downslope. In the case where a glacier enters the sea, it may be pushed sufficiently seaward that it is afloat.

2.6.1.2 Ice Shelves are defined as floating ice sheets of considerable thickness with a freeboard greater than 2 m. Ice shelves are distinguished from floating glaciers in that ice shelves are usually of great horizontal extent. An ice shelf can be created as a result of a number of processes or even the combination of several processes including: annual snow accumulation on the ice surface, growth of ice on the undersurface, and the seaward extension of glaciers from the surrounding land. The surface of an ice shelf is usually flat or gently undulating.

### 2.6.2 Nomenclature of Glaciers and Ice Shelves.

2.6.2.1 Glacier Tongue. This term is used to depict the seaward projection of a glacier. In some cases, portions of glacier tongues can be afloat. In Antarctica, glacier tongues may have dimensions on the order of tens of km in length.

2.6.2.2 Ice Wall. This term depicts the seaward margin of a glacier extending into the sea but which is not afloat. Thus, an ice wall extends to the sea floor.

2.6.2.3 Ice Front. This term depicts the seaward margin of either a floating glacier or an ice shelf.

### 2.6.3 Nomenclature of Ice Calved from Glaciers and Ice Shelves.

The breaking away of a floating ice mass from an ice wall, an ice front, or another floating ice mass is called calving. In the following paragraphs the various designations for calved ice will be defined.

2.6.3.1 Icebergs. A massive piece of ice calved from an ice wall or ice front. Icebergs are usually irregular in shape and may be described as tabular, dome-shaped, sloping, pinnacled or weathered.

2.6.3.2 Tabular Berg and Ice Island. These terms have essentially identical definitions. Their distinction is that of location. Ice islands are found in the arctic ice pack while tabular bergs are found in the ice and open ocean surrounding Antarctica. Both features are flat-topped icebergs and can range in size from a few thousand square meters to over 100 square kilometers. They are usually characterized by a regularly undulating surface which gives them a ribbed appearance when viewed from above. Ice islands are calved from arctic ice shelves, while tabular bergs are usually calved from antarctic ice shelves and sometimes antarctic glaciers. Ice islands have a maximum freeboard on the order of 3-5 m while tabular icebergs can have significantly greater freeboards.

2.6.3.3 Bergy Bit. This term is used to signify a large piece of calved ice with a freeboard between 1 and 5 m and with an area between 100 and 300 m<sup>2</sup>.

2.6.3.4 Growler. This term designates a piece of calved ice smaller in size than a bergy bit (less than 1 m freeboard and less than 100 m<sup>2</sup> in extent).

### SECTION 3. PHYSICAL CHARACTERISTICS OF SEA ICE

#### 3.1 ALBEDO

One of the most obvious physical characteristics of sea ice is the relative amount of visible light reflected from its surface. As the descriptions of ice types have shown, this factor - known as albedo - is an important quality when determining the early stages of ice growth. Here we will briefly summarize the relationship between albedo and ice thickness. This deals only with the albedo (in the visible spectrum) and ice thickness.

<u>Albedo</u>	<u>Thickness</u>	<u>Type Designation</u>
very low, ice areas appear dark against water surface	ice crystals contained within the water column up to 5 cm in thickness	New ice forms up to dark nilas stage
low, ice appears dark gray	between 5-10 cm in thickness	light nilas
moderately low, ice appears gray	between 10-15 cm in thickness	gray ice stage of young ice
moderate, ice appears light gray	between 15-30 cm in thickness	gray white ice stage of young ice
moderately high, ice appears very light gray when compared against snow covered ice	greater than 30 cm in thickness	first-year ice

Albedo values are tabulated, for example, in Shine and Henderson-Sellers, (1985) and Grenfell and Maykut, (1977).

#### 3.2 SALINITY

The salinity of sea ice is an important characteristic. It plays a large role in determining the strength of ice and to some extent, reflects the age of a particular piece of ice.

Although sea water has a salinity in the vicinity of 35% , ice grown from sea water seldom has a salinity greater than 1/3 or 1/4 this value. In fact, frazil ice crystals are nearly pure water. However, when a mass of frazil crystals congeal to form nilas, they entrap pockets of sea water between them, some of which may have an elevated salt content caused by the expulsion of salts during the freezing of the frazil crystals. Mea-

surements have shown that the top few centimeters of ice usually contain 8 to 10% because of this process. In general, the depth of this layer depends on the thickness of the frazil ice layer at the time of formation of nilas. This, in turn, is usually related to winds and sea state. (The deeper the surface supercooling layer, the more frazil ice formed. The greater the sea agitation, the longer frazil crystals accumulate before congealing.)

After the formation of the first crust of ice on the sea surface, the freezing process changes. In order to grow new ice on the undersurface of the nilas, heat must be conducted through the ice layer to the atmosphere. This will generally be an orderly process and will not result in a soup of frazil crystals in the water below the ice. The growth of crystals becomes much more orderly. The crystals are oriented so that the plates which form extend downward with their flat sides having a strong tendency to arrange themselves in a parallel fashion. The result of this growth pattern is to create the appearance of many vertical columns of ice grown together. This zone is called the columnar region. As a result of this more orderly growth pattern, less dissolved salt is entrapped and an average salinity of around 6‰ results after the crystals have grown in size sufficiently to fill most of the voids.

However, at any given time there will be a layer of incomplete crystal growth at the bottom of a growing ice cover. At its very bottom, this layer has the appearance of an open lattice. Since this lattice forms the skeleton around which ice crystals will grow, it is called the skeletal layer. Because this layer contains pockets of salt water which are not yet excluded, its salinity is somewhat higher (around 10‰) than it will be after it becomes part of the columnar zone. Hence, at any given time, one would expect to find a c-shaped profile of salinity with depth through a growing ice cover, with salinities around 10‰ at the top and bottom of the "c" and salinities around 6‰ in the middle of the "c".

3.2.1 Variations in Salinity. It should be pointed out that the description just presented is quite general in nature. For instance, the salinity in the center of the profile just discussed can easily vary by +2‰ as the result of a number of factors, but largely related to the rate

of crystal growth at the time of freezing and warming cycles during the winter. Furthermore, measurements have shown that the salinity at a given ice depth can vary by  $\pm 0.6\%$  on the average over distances of a meter or two. Finally, not all water which becomes sea ice has a salinity as high as  $35\%$ , and the ice which is subsequently formed from this water will have a correspondingly lower salinity.

3.2.2 Salinity vs. Age of Ice. It is well known that old ice (i.e. ice older than one melt season) has a greatly reduced salt content compared to first-year ice. The precise process by which this "freshening" of the ice takes place is a matter of current debate and may be actually the result of a number of processes. The end result, however, is a floe with nearly no salinity above sea level and a gradual increase to a salinity of around  $3.0$  to  $3.5\%$  with increasing depth below sea level. The overall average salinity for such a floe has a limiting value somewhere in the vicinity of  $2\%$ .

### 3.3 STRENGTH OF SEA ICE

Obviously the strength of sea ice plays a major role with regard to navigation in icy waters. This characteristic is also an important factor to be considered in predicting sea ice behavior. The strength depends a great deal on the particular stress applied. The resistance to compressive stresses (the compressive strength) is much greater than the resistance to tensile stresses (the tensile strength). As a result, for any given thickness the ice is much more easily pulled apart than piled together.

3.3.1 Salinity and Temperature. The strength of sea ice is known to depend on its temperature and salt content. However, the measurement of ice strength is a difficult process, and the exact form of the relationship between ice strength and these factors has not been determined. In general, sea ice is weaker than freshwater ice and its strength increases as the salt content decreases. Furthermore, the strength of sea ice increases as its temperature decreases.

The theoretical concept describing the strength of sea ice is based on the observation that as ice is formed from sea water, the dissolved salts are excluded from the ice crystals during the freezing process.

However, some of the salts are trapped in brine pockets (giving first-year ice an overall salt content of around 5%). Because of the salt content of these brine pockets, their freezing point is lowered and, therefore, they remain unfrozen. These unfrozen pockets yield an ice which is weaker than ice without pockets such as freshwater ice.

Theoretical models of ice strength vs temperature (Assur, 1958) have been based on the physics of processes within the brine pockets as the ice becomes colder. In general, as the brine within the pockets becomes colder, water is frozen out, creating smaller brine pockets and, thereby, increasing the strength of the ice.

In addition, from chemical principles it is known that when temperatures are sufficiently low, the dissolved salts precipitate out in the form of solid hydrates. It has been proposed that these solid hydrates add to the overall strength of the ice.

The first salt hydrate to precipitate should be that of sodium sulfate,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$  (the sulfate ion is the second most abundant dissolved salt ion in sea water at a concentration of 2.6%, compared to a concentration of 19% for the chloride ion). Starting at  $-8.2^\circ \text{C}$  the strength of ice should be increased by the presence of this precipitate. However, it is not clear how rapidly the strength increases.

The next salt hydrate to precipitate should be the hydrate of sodium chloride,  $\text{NaCl} \cdot 2\text{H}_2\text{O}$ . Theoretically, the precipitate of this hydrate should increase ice strength rather abruptly starting at  $-22.9^\circ \text{C}$ .

Because ice strength is difficult to measure, and because of variations from sample to sample, there is a wide variation in measured strengths for each temperature. As a result, the data do not resemble lines, but rather envelopes. From the shape of the envelopes, it can be seen that ice strength increases with colder temperatures, but it is not possible to tell whether the formation of solid precipitates are responsible or whether the increase in strength is a result of the general decrease in the size of the brine pockets.

Figure I-1 (p. 7) shows data relating the tensile strength of ice and temperature for ice of two salinities. The strength can be seen to

increase as temperatures are lowered and to increase more rapidly for ice with low salinities. The lower salinity used here (1-2‰) corresponds to multiyear ice while the upper salinity (7-9‰) corresponds to newly formed young ice. First-year ice has a salinity content between these two ranges. The ice samples used in these measurements were taken so that this strength measurement applies to the vertical direction within the ice.

It should be borne in mind that only the top surface of an ice layer will be at air temperature (or even higher if there is a snow cover) and that the temperature will increase down through the ice reaching the temperature of the water underneath (somewhere around  $-1.9^{\circ}\text{C}$ ) at the bottom surface. Furthermore, since snow has a heat conductivity only 1/10 that of ice, the temperature at the ice surface beneath the snow can be considerably greater than the air temperature, and the entire ice layer will be correspondingly warmer and, therefore, weaker.

3.3.2 Age. Since salinity decreases with age, it is reasonable to anticipate that strength increases with age. Figure I-1 shows that old ice can be between 10 and 40% stronger than first-year ice (depending on temperature and whether one is comparing strengths above or below sea level). However, this comparison is valid only for an ice floe. In the case of a pressure ridge or floeberg, the increase of strength with age can be much more pronounced. This results from the filling of voids both above and below sea level with fresh water ice during the melting and re-freezing process. By this means, the relatively weak bonding between ice blocks in these features is greatly increased with age.

3.3.3 Loading Rate. Ice is a plastic substance and will deform under stress. As it deforms, the force required to break it becomes greater. If stress is applied slowly, its breaking strength becomes greater and it becomes able to withstand a larger stress before failing than if the stress were applied suddenly.

3.3.4 Strength vs. Size of Sample. The strength of sea ice depends a great deal on the size of the sample being measured (or the scale of the measurement). A great deal of work has been done in laboratories where relatively small samples (on the order of 10-100 cm in dimension) can be

placed under stress in relatively controlled conditions. The failure strength is the pressure (force per unit area) at which the ice sample "fails" and ceases to offer resistance to applied stress. The greatest ice strengths are measured at this laboratory scale. This is largely because the samples tested have the greatest chance of being homogenous with few internal flaws along which failure can take place.

The next sample size is what might be called the field test scale. This size is determined by the amount of stress which can be applied to an ice test sample in the field under conditions which allow accurate measurement of the stress. This sample size varies over the range of 1 to 10 m in dimension. Some control over sample composition and thickness is possible, but other factors such as temperature cannot be controlled. Although such tests are more realistic, it is often difficult to acquire data over the entire range of desired parameters. The measurements of ice strength at field test scale tend to be lower than laboratory scale strength measurements because the samples generally contain more flaws and are less homogeneous than laboratory specimens.

A third sample size which produces crude but useful strength values for operational uses is on the order of 100 to 300 m. This sample size category might be called an operational scale. At this scale, floes are instrumented with stress transducers in anticipation of the floe either encountering a natural obstruction or the ramming of the floe by an ice-strengthened ship. These are very realistic measurements when considered full-scale tests (that is, the strength of a floe when encountering a man-made obstruction), but there are many difficulties involved.

The fourth sample size category is what would be called a regional scale. This is the scale generally of most interest to ice analysts. At this scale, the strength of an area of ice with dimensions on the order of 10 to 50 km is important. Typically, a region of ice not only contains floes of various thicknesses, but also leads and polynyas. Often large lead systems will be found frozen to states of thickness less than the first-year category (i.e. less than 30 cm). Obviously, as the ice is compressed, leads and polynyas will be closed rather easily. Following this, thinly frozen leads will be closed with the consequent ridging of the ice in the lead. Next, leads with thicker ice and thin floes will be



piled in large ridges or hummock fields. Thus, a compressive force on the ice will encounter an increasing ice strength as the pack is compressed. This is a rather complicated strength relationship which requires measurements on a regional scale. The stress (force per unit area) on the ice is obtained by measurement of winds on the top surface and oceanic currents beneath. A new quantity, the strength modulus is found by measuring the strain (amount of compaction) from satellite imagery and baseline measurements and dividing the stress by the strain. True failure does not take place. (The entire ice pack does not suddenly shatter and pile up.) Instead, the stress required to produce further compaction increases as the compaction (strain) increases.

Numerically, the relationship can be expressed as follows:

$$\text{stress} = K \cdot \text{strain}$$

K is a property of the ice pack. For purely compressive forces, this equation implies the following relationship: the stress (force per unit area) equals the strength modulus, K, (also in units of force per unit area) times the strain (the compaction expressed as a fraction). For any given strain, a strength is implied. For instance, if the ice pack is compressed 5 km in 100 km, we have a strain of 1/20 and:

$$\text{strength (stress within the ice)} = K \cdot 1/20.$$

In practice, if one assumes the thickness of the ice pack to be its average thickness, the regional strength it acquires through compression never comes close to the failure strength of a laboratory sample. However, in those areas of the pack where stress is concentrated and ice is crushed and piled up, the stress applied is clearly greater than the ice failure strength.

3.3.5 Crystal Orientation. Another interesting property of sea ice is the orientation of the individual crystals of ice. As explained earlier, ice crystals form in flat platelets. These platelets result from a preferential growth pattern in the structure of the crystal. In order to provide a coordinate system for reference purposes, the direction perpendicular to that flat sides of the crystal is called the c-axis of the crystal. Thus, we can say that the crystal tends to grow in directions perpendicular to the c-axis.

When frazil crystals collect to form dark nilas, the c-axes are mostly in the horizontal plane (the crystals stand vertically) but they are oriented randomly in that plane (looking down, the platelets have random alignment). However, several observations of the columnar ice forming below the initial layer indicate that often after a transition zone, the c-axes are aligned, meaning that the surfaces of ice crystal platelets are growing parallel to each other. It is generally thought that this results from a preferential growth of ice crystals in the direction of the motion of the water which supplied material for crystal growth. In this way, the c-axis orientation within a floe would become a record of the floe's orientation relative to the currents beneath the ice.

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# Marginal Ice Zone Bibliography

## Introduction

This bibliography covers several major areas of marginal ice zone research: oceanography, ice, meteorology, remote sensing, and acoustics. Only biology is specifically excluded. The period of coverage extends from the early twentieth century through 1984.

We have attempted to be as comprehensive as possible by searching a variety of data sources and using broad subject categories. The major sources searched were:

CITATION Data Base (WDC/NSIDC)  
Cold Regions Bibliography  
Compendex  
Dissertation Abstracts  
Groarchive  
Meteorological and Geoastrophysical Abstracts  
NTIS (National Technical Information Service)  
Oceanic Abstracts.

The bibliography is presented in two sections. The first listing is by subject category. The six category headings used are:

Oceanography . . . . .	p.31	Remote Sensing . . . . .	p.103
Ice . . . . .	p.49	Acoustics . . . . .	p.114
Meteorology . . . . .	p.89	General . . . . .	p.117

The second listing is an alphabetical sort by first author. Because we do not have all of the original material in hand, we cannot be certain of the completeness of each citation although every effort has been made to ensure accuracy.

We would appreciate your comments on the bibliography - on citations we have not included, sources not searched, or subject areas that were not adequately covered. We hope to keep this bibliography current and your suggestions are welcome.

Ann M. Brennan  
Compiler

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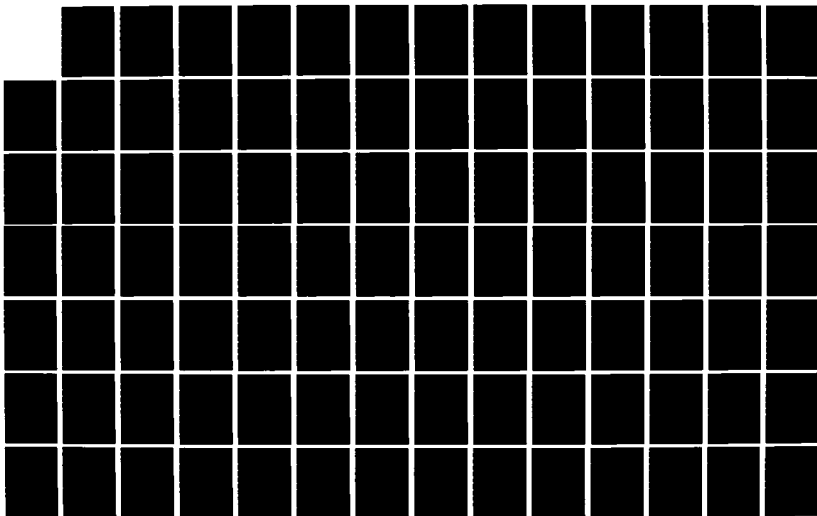
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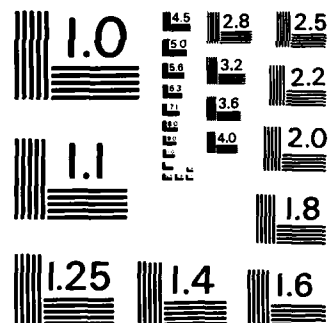
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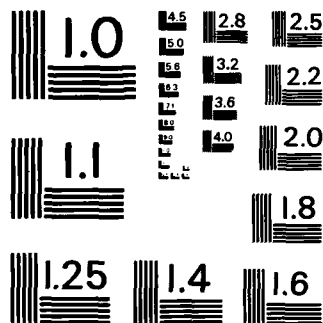
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## NOTE

### DATA MANAGEMENT FOR THE MIZEX-EAST PROGRAM

#### Introduction

The National Snow and Ice Data Center (NSIDC)<sup>1</sup> assumed responsibility for the management of data from the Marginal Ice Zone Experiment (MIZEX)-East on 1 October 1983. The objectives within this management task include the following:

1. Establish and implement a data accession and archival program.
2. Establish and coordinate data exchange standards.
3. Coordinate data flow from principal investigators to the participating data centers and/or other principal investigators.
4. Promote and facilitate interchange of data management information between principal investigators and other scientific staff.

All data accession and archival procedures are compatible with those of the National Geophysical Data Center (NGDC), a facility of NOAA's National Environmental Satellite, Data, and Information Service. Specific technical advice pertinent to MIZEX data are supplied to NSIDC, on request, by the MIZEX Science Group, and in particular, the Committee on Data Management.

The data management plan is an example of the effort to address the task of data management at an early stage in a large research project and should provide a useful example for future projects. Although the data sets are currently available only to MIZEX investigators, this report on NSIDC activities may be of interest to our readers as illustrative of the widening role of NSIDC/WDC-A for Glaciology in data management for snow and ice phenomena.

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<sup>1</sup>NSIDC was designated by NOAA/NESDIS in 1982 as a center colocated with WDC-A for Glaciology in the University of Colorado, serving specific national needs for archiving/management of snow and ice data.

### Data Management Activities

During the first two years of the project, NSIDC has worked on the development and implementation of the MIZEX Data Management Plan, to satisfy the task objectives. The Data Management Plan was approved by the Data Management Committee and was published in Chapter VIII of the MIZEX 1984 Operations Manual.

A computerized listing of all data sets and reports submitted to NSIDC has also been prepared. This data inventory is posted on the MIZEX Bulletin Board within the electronic mail system TELENET and is available to all MIZEX personnel on a continuous basis. The inventory is updated approximately once every two months, depending on the number of accessions. The catalog is a part of the overall data base management system and can be searched by categories such as author, discipline, data type, platform, etc.

All data sets in the catalog listing are available to the MIZEX investigators on request as well as to certain scientific staff of the U.S. Navy. Any data requests coming from outside this group must first receive approval from the relevant principal investigator except in those cases where documents are clearly specified to have unlimited distribution. Hardcopy data, manuscripts, and reports are duplicated at NSIDC and mailed to the party making the request with minimal delay, usually within one to three days. Requests for magnetic tapes are handled through duplicating copies of originals which generally requires no more than 3 to 5 days.

With regard to magnetic tape data, a standardized procedure has been adopted to verify, copy, label, and store each incoming tape within the established system operated by NGDC in Boulder. All original data tapes, complete with supporting documentation, are archived at NSIDC while the verified copies are located within the tape storage facility of NGDC. All tapes are scanned at appropriate intervals to maintain their integrity.

### Future Plans

Upon completion of the first two years of the MIZEX Data Management Project, the tasks outlined in the above sections have been established and have become operational. As data continue to arrive at NSIDC the management tasks will largely shift from data base development to the more

routine tasks of accession, archival, and distribution of data within the framework of the existing system.

In the future NSIDC will continue to provide the following services:

- 1) NSIDC will continue to give the highest priority to maintaining contact with all MIZEX personnel and to familiarizing them with the data transfer, storage, and exchange program. The MIZEX Data Manager will continue to consult directly with the Data Management Committee regarding the completeness of the data from the 1983 and 1984 field experiments. Discipline Chairmen will be asked to comment on any data they feel have not been included in the 1983-1984 catalog within their field and NSIDC will attempt to obtain those data sets.
- 2) NSIDC will continue to service data requests, update the data inventory contained in the MIZEX Bulletin Board, and to assist all principal investigators and associates in the location, acquisition, and transfer of data as required.
- 3) All MIZEX journal articles and published reports will be contained in the comprehensive Marginal Ice Zone Bibliography which has been prepared by NSIDC and is contained in this issue of Glaciological Data. All references in this bibliography are linked to NSIDC's CITATION data base which allows complete computerized access and retrieval.
- 4) An expanded data catalog inventory will be maintained which will contain additional details regarding the location, time frame, frequency, and measurement system for each data set as well as more complete references for published reports. It will be possible to key data searches to either the brief or extended form of the catalog depending on what level of detail is required for the initial search.
- 5) In conjunction with 4), a document coding system has been developed which assigns a brief alphanumeric code to each data item produced within the MIZEX program. This system allows all types of data to be easily identified and tracked, whether they might be field notes, photographs, magnetic tapes, maps, charts, or published reports. This index code serves the specific needs of MIZEX and is compatible with existing systems at NSIDC and the National Geophysical Data Center.

- 6) A set of Defense Meteorological Satellite Program visible and infrared imagery which covers part of the 1983 MIZEX field experiment has been assembled from the NSIDC archives. We are currently in the process of expanding this coverage to include the entire 1983 as well as the 1984 experiment.

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# GLACIOLOGICAL DATA SERIES

Glaciological Data, which supercedes Glaciological Notes, is published by the World Data Center-A for Glaciology (Snow and Ice) several times per year. It contains bibliographies, inventories, and survey reports relating to snow and ice data, specially prepared by the Center, as well as invited articles and brief, unsolicited statements on data sets, data collection and storage, methodology, and terminology in glaciology. Contributions are edited, but not refereed or copyrighted. There is a \$5 shelf stock charge for back copies.

Scientific Editor: Roger G. Barry

Technical Editor: Ann M. Brennan

The following issues have been published to date:

- GD- 1, Avalanches, 1977
- GD- 2, Parts 1 and 2, Arctic Sea Ice, 1978
- GD- 3, World Data Center Activities, 1978
- GD- 4, Parts 1 and 2, Glaciological Field Stations, 1979, Out of Print
- GD- 5, Workshop on Snow Cover and Sea Ice Data, 1979
- GD- 6, Snow Cover, 1979
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- GD- 8, Ice Cores, 1980, Out of Print
- GD- 9, Great Lakes Ice, 1980, Out of Print
- GD-10, Glaciology in China, 1981
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- GD-13 Workshop Proceedings: Radio Glaciology; Ice Sheet Modeling, August 1982
- GD-14 Permafrost Bibliography, 1978-1982, July 1983
- GD-15 Workshop on Antarctic Climate Data, April 1984
- GD-16 Soviet Avalanche Research; Avalanche Bibliography Update; 1977-1983, November 1984

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Barry, R.G., ed. (1984) Snow and Ice. Chapter 9, CODATA Directory of Data Sources for Science and Technology, E.F. Westrum, ed. New York, Pergamon Press. (CODATA Bulletin, no. 53, 87p.

This chapter provides an overview of the principal agencies and institutions involved in glaciological data collection. It covers information relating to all forms of terrestrial snow and ice - snow cover, freshwater and sea ice, glaciers, ice sheets, and ground ice. The principal listing is by country, and subject and name indexes are provided.

The information was compiled from a survey distributed by the World Data Center A for Glaciology (Snow and Ice) to addresses of centers, agencies, and institutions available through the mailing lists of the WDC-A and the International Glaciology Society.

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